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CLIC – Note – 1144

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Abstract

Nominal operating conditions for the Compact Linear Collider (CLIC) 380 GeV requires 72 MV/m loaded accelerating gradients for a 180 ns flat-top pulse. Achieving this requires extensive RF conditioning which past tests have demonstrated can take several months per structure, when conditioned at the nominal repetition rate of 50 Hz. At CERN there are three individual X-band test stands currently operational, testing up to 6 structures concurrently. For CLIC's 380 GeV design, 28,000 accelerating structures will make up the main linac. For a large scale conditioning programme, it is important to understand the RF conditioning process and to optimise the time taken for conditioning. In this paper, we review recent X-band testing results from CERN's test stands. With these results we investigate how to optimise the conditioning process and demonstrate the feasibility of pre-conditioning the structures at a higher repetition rate before installation into the main linac.

Geneva, Switzerland
29 April 2018

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMK103

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Abstract

Nominal operating conditions for the Compact Linear Collider (CLIC) 380 GeV requires 72 MV/m loaded accelerating gradients for a 180 ns flat-top pulse. Achieving this requires extensive RF conditioning which past tests have demonstrated can take several months per structure, when conditioned at the nominal repetition rate of 50 Hz. At CERN there are three individual X-band test stands currently operational, testing up to 6 structures concurrently. For CLIC's 380 GeV design, 28,000 accelerating structures will make up the main linac. For a large scale conditioning programme, it is important to understand the RF conditioning process and to optimise the time taken for conditioning. In this paper, we review recent X-band testing results from CERN's test stands. With these results we investigate how to optimise the conditioning process and demonstrate the feasibility of pre-conditioning the structures at a higher repetition rate before installation into the main linac.

INTRODUCTION

In preparation for the 380 GeV Compact Linear Collider (CLIC), testing of X-band high gradient accelerating structures is ongoing at CERN. Before injection of the first bunches, the high gradient accelerating structures require RF conditioning to achieve the 72 MV/m loaded gradients. The testing programme at CERN has continued with the CLIC-G (3 TeV) based structures where structures are conditioned in excess of 100 MV/m. This is in order to complete this study and allowing the results from the tested structures to be compared to existing benchmark data. In the past, conditioning of the structures has taken several months per structure [1]. In the CLIC-380 design, approximately 28,000 structures make up the main linac and therefore optimising the efficiency of structure conditioning is crucial [2].

Determining an optimal conditioning strategy is an important priority for the CLIC accelerating structure development programme. The current strategy involves conditioning to nominal gradient at a constant pulse length then repeating the process at longer pulse lengths, all with a constant BDR [3]. Once the gradient and pulse length are achieved, the structure is left to condition down to the nominal BDR of 3×10^{-7} breakdowns/pulse/m [2]. The BDR set point during conditioning, generally around 2.5×10^{-4} breakdowns/pulse/m, is three orders of magnitude above the nominal minimum BDR. To determine the time it will take to reach the acceptable BDR level, we investigate the BDR decay trend for structures pulsing at a constant gradient and pulse length. Figure 1 displays the BDR decay of the T24 Open and TD26CCR05 structure each tested on the Xbox 2 X-band test stand [4]. The steady decay of the BDR follows an inverse power law and decreases by approximately a factor of ten per decade though experiences transient jumps in the BDR during breakdown clusters. A possible strategy to reduce the time required for conditioning is to increase the repetition rate of the conditioning and also to pre-condition the structures before installation into the main linac. Below we will investigate the feasibility of this high repetition rate pre-conditioning from test results performed on CERN's X-band test stands.

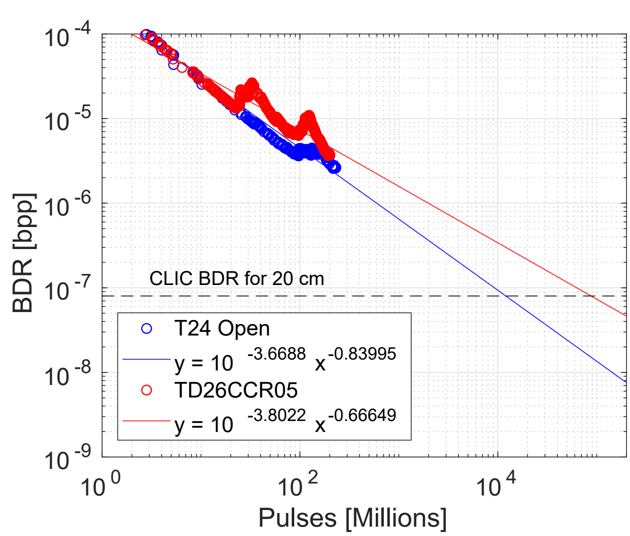

Figure 1: BDR decay rate during conditioning for the TD26CC R05 and T24 Open structures.

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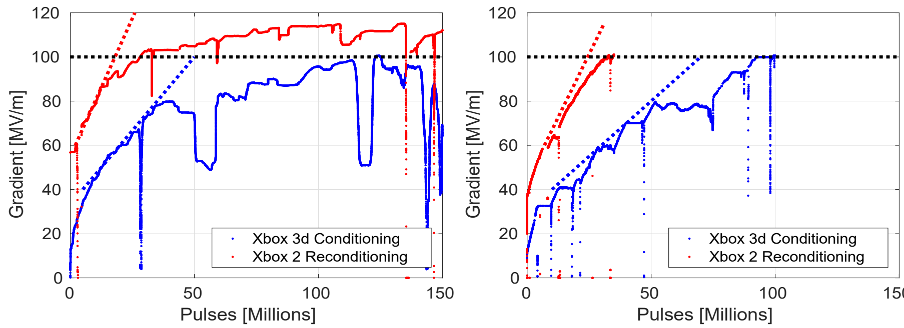

Figure 2: A comparison of the conditioning of the T24 PSI N1 (left) and N2 (right) structures which each started the first phase of conditioning in Xbox 3 which subsequently continued in Xbox 2. Tangent lines compare the conditioning rate at 70 MV/m.

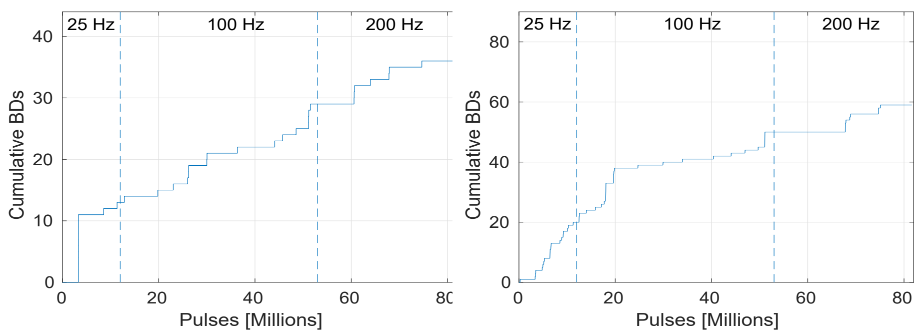

Figure 3: Cumulative breakdowns during conditioning of the T24 PSI (left) and TD24 SiC (right) at 25, 100, and 200 Hz.

GRADIENT RECOVERY AFTER EXPOSURE TO AIR

With 28,000 individual structures and a nominal repetition rate of 50 Hz, conditioning of the structure installed in the main linac isn't the most efficient method of conditioning. It has been suggested that structures may be pre-conditioned in separate test stands before installation into the main linac [5]. For the conditioning of the T24 PSI N1 and N2 prototypes, the structures began conditioning in Xbox 3. The Xbox 3 test stand can operate with a pulse repetition rate up to 400 Hz and therefore offers the possibility of faster conditioning. Each structure was able to achieve an unloaded gradient of 100 MV/m, before being limited by the achievable power of Xbox 3 [6, 7]. Subsequently the structures were moved to Xbox 2, which can operate with a much greater input power than Xbox 3, where they continued and concluded their conditioning.

In Fig. 2, the first phase of conditioning in Xbox 3 and second phase of conditioning in Xbox 2 are demonstrated for the T24 PSI N1 and N2 structure, separating, by overlaying the two phases of conditioning. At the start of the second phase of conditioning, we observed that the structures could begin conditioning at 57 MV/m and 40 MV/m for the N1 and N2, respectively. Two dashed tangent lines demonstrate the appoximate rate of conditioning at 70 MV/m. It was found that the conditioning rate was 2.5 and 2.3 times greater at 70 MV/m for the second phase of conditioning compared to that of the structure yet to see high power (first phase). For the structures in phase 1, the conditioning took approximately the same number of pulses (100 million) to reach 100 MV/m, after adjusting for the power drops on the N1's phase 1 conditioning at 50 and 115 million pulses resulting from radiation issues. For the previously conditioned structures, phase 2, the 100 MV/m unloaded gradient was achieved in approximately 25-30 million pulses. Given the higher initial power and steeper conditioning curve, and that the structures reached the 100 MV/m in fewer pulses, we found that the conditioning is partially retained in the structure, despite the exposure to air.

PULSE REPETITION RATE VS BDR

The klystrons in Xbox 3 can operate at pulse repetition rates up to 400 Hz, allowing pulsing of the each line up to 200 Hz [8]. For pre-conditioning of the structures, it has been proposed that pulsing would operate at repetition rates well above the nominal CLIC parameters to reduce the

Table 1: BDR measured for the SiC structure for variations in the pulse repetition rate.

Structure	Rep. Rate [Hz]	BDR [bpp]	Uncertainty [bpp]
SiC N2	25	1.08×10^{-6}	$\pm 3.0 \times 10^{-7}$
	100	3.9×10^{-7}	$\pm 9.7 \times 10^{-8}$
	200	2.4×10^{-7}	$\pm 9.12 \times 10^{-8}$
PSI N2	25	1.66×10^{-6}	$\pm 3.73 \times 10^{-7}$
	100	7.317×10^{-7}	$\pm 1.34 \times 10^{-7}$
	200	3.1×10^{-7}	$\pm 1.03 \times 10^{-7}$

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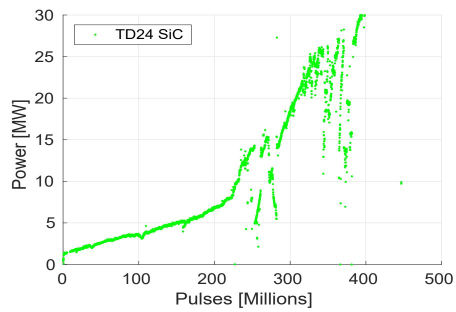

Figure 4: Conditioning curve of the TD24 R05 SiC whose progress was limited due to the algorithm.

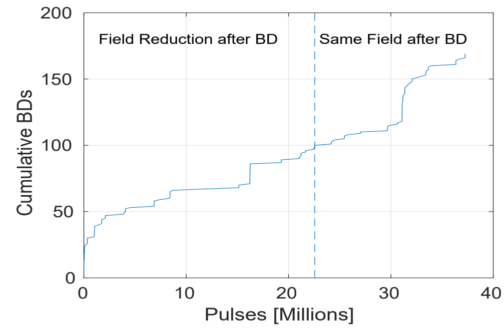

Figure 5: Cumulative Breakdown curve for operation with and without field reduction after breakdowns.

required conditioning time. Increasing the repetition rate increases the average power dissipated in the structure and it is important to undestand how this affects the BDR. Using the damped Silicon Carbide (SiC) structure and the undamped PSI structure, pulsing at constant power and pulse length was performed at three pulse repetition rates. Figure 3 displays the cumulative breakdowns for 82 million pulses. Summarising the results, Table 1 displays the measured BDR for the three repetition rates. For the SiC structure, the BDR at 25 Hz and 100 Hz appeared to decrease despite the increased average power. For 200 Hz pulsing, the BDR remained the same as the 100 Hz repetition rate within statistical uncertainty. The BDR on the PSI structure began at the higher breakdown rate of 1.66×10^{-6} bpp at 25 Hz, expected to be the result of the initial change in power. Subsequent pulsing at 100 and 200 Hz continued to decrease in BDR due to conditioning. With the increase in average power, there was no evidence of a BDR increase for a pulse repetiton rate change.

LIMITED RATE OF CONDITIONING DUE TO ALGORITHM

Conditioning in the X-band test stands is controlled by an algorithm previously described in [3]. Checking the BDR every 180 seconds, the power increases in 10 kW steps when the BDR is below the selected setpoint. The rate of power increase is dependent on the BDR limit, the loop length, and the power step size. During the conditioning of the first structure on Xbox 3, it was observed that the rate of RF conditioning was unusually slow and linear in comparison to past structures [1]. Figure 4 displays the conditioning of the TD24R05 SiC N1 structure. For the first 200 million pulses with an increment loop length of 30,000 pulses, power step of 10 kW, and BDR limit of 3×10^{-5} bpp, it can be seen that the increase in power is 7 MW over 200 million pulses. At 200 million pulses, the BDR limit was changed to 1×10^{-4} bpp and a loop length of 7500 pulses. A clear increase in the rate of conditioning is visible with the distinct curvature of RF conditioning. This demonstrates the algorithm's ability to limit the progress of the structure's conditioning. The drops at 250 and 350 million pulses are the result of conditioning of the waveguide network.

RECOVERY AFTER BREAKDOWN

After breakdown events in the X-band test stands, it has become common practice to interlock briefly before recommencing pulsing at a reduced input power then steadily returning to the set power level after a few hundred pulses. This reduction in power is meant to reduce the likelihood of a follow-up breakdown. For CLIC, this reduction in field after a breakdown is undesirable as it will affect the luminosity of the machine by increasing the downtime due to RF breakdown. During testing of the TD26CCR05 structure, modifications to the algorithm allowed continuous pulsing after a breakdown event, with the interlock and field reduction to be enabled only after two consecutive breakdown pulses. Figure 5 displays the cumulative breakdowns for the normal conditioning algorithm and for the running without this field reduction. Switching to this new conditioning algorithm didn't appear to affect the BDR though further testing will be necessary to determine the long-term feasibility of this pulsing strategy.

CONCLUSION

A structure conditioning strategy for the high gradient accelerating structures of CLIC is crucial for cost minimisation. Conditioning the structures while installed in the main linac will require several months of RF conditioning, if pulsed at the nominal repetition rate, although this can occur in parallel with beam commissioning. Preconditioning structures at a higher repetition rate in separate test-stands and then installing them into the main linac has been demonstrated as a possible solution to reduce the overall conditioning time. Results demonstrated that higher repetition rate conditioning didn't lead to a higher breakdown rate and conditioning was partially maintained in a structure when moved between test-stands. This opens up the option for pre-conditioning structures before installation. If the structure conditions faster than the algorithm increases the input RF power, the conditioning is retarded by the algorithm. Finally, algorithmic reductions of the field strength after RF breakdowns aimed to prevent further RF breakdowns during conditioning, though this technique isn't desirable for an operational CLIC. Initial tests demonstrated that the continuation of puls-

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ing after an RF breakdown is possible without a noticeable BDR increase.

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